ACOUSTIC FORCE GENERATION BY
AMPLITUDE MODULATING A SONIC BEAM

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Background Of The Invention

The field of the invention is the detection and imaging of objects using acoustic beams.

In the field of medical imaging there are a number
10 of modes in which ultrasound can be used to produce images of objects within a patient. The ultrasound transmitter may be placed on one side of the object and the sound transmitted through the object to the ultrasound receiver placed on the other side
15 ("transmission" mode). With transmission mode methods, an image may be produced in which the brightness of each image pixel is a function of the amplitude of the ultrasound that reaches the receiver ("attenuation mode"), or the brightness of each pixel is a function of
20 the time required for the sound to reach the receiver ("time-of-flight" or "speed of sound" mode). In the alternative, the receiver may be positioned on the same side of the object as the transmitter and an image may be produced in which the brightness of each pixel is a
25 function of the amplitude of the ultrasound reflected from the object back to the receiver ("reflection", "backscatter" or "echo" mode). In another mode of operation ("Doppler" mode) the movement of the object is detected and imaged by measuring the phase of the
30 ultrasound reflected from the object back to the receiver.

-1-

In all of these medical imaging applications ultrasonic waves are transmitted and ultrasonic waves are received. The higher sonic frequencies enable precise beams to be formed in both the transmit and receive
5   modes. Ultrasonic transducers for medical applications are constructed from one or more piezoelectric elements sandwiched between a pair of electrodes. Such piezoelectric elements are typically constructed of lead zirconate titanate (PZT), polyvinylidene diflouride
10 (PVDF), or PZT ceramic/polymer composite. The electrodes are connected to a voltage source, and when a voltage waveform is applied, the piezoelectric elements change in size at a frequency corresponding to that of the applied voltage. When a voltage waveform is applied, the
15 piezoelectric elements emits an ultrasonic wave into the media to which it is coupled at the frequencies contained in the excitation waveform. Conversely, when an ultrasonic wave strikes the piezoelectric element, the element produces a corresponding voltage across its
20 electrodes. A number of such ultrasonic transducer constructions are disclosed in U.S. Patent Nos. 4,217,684; 4,425,525; 4,441,503; 4,470,305 and 4,569,231.

When used for ultrasonic imaging, the transducer typically has a number of piezoelectric elements arranged
25 in an array and driven with separate voltages (apodizing). By controlling the time delay (or phase) and amplitude of the applied voltages, the ultrasonic waves produced by the piezoelectric elements (transmission mode) combine to produce a net ultrasonic
30 wave that travels along a preferred beam direction and is focused at a selected point along the beam. By controlling the time delay and amplitude of the applied voltages, the beam with its focal point can be moved in a plane to scan the subject. A number of such ultrasonic
35 imaging systems are described in U.S. Patent Nos. 4,155,258; 4,155,260; 4,154,113; 4,155,259; 4,180,790;

-2-

4,470,303; 4,662,223; 4,669,314; 4,809,184; 5,081,995 and 5,492,121.

The acoustic radiation force exerted by an acoustic wave on an object in its path is a universal phenomenon common to all forms of radiated energy. When a beam of light is absorbed or reflected by a surface, a small force is exerted on that surface. The same is true for electromagnetic waves, transverse waves on an elastic string, and surface waves on a liquid. This force is produced by a "radiated pressure" and a complete disclosure of this phenomenon is set forth by G.R. Torr, "The Acoustic Radiation Force", Am. J. Phys. 52(5), May 1984.

The measurement of radiation force exerted by sound waves has become important in recent years to determine the power outputs of medical imaging ultrasonic transducers, Beissner, K., "Measurement Techniques In Ultrasonic Exposimetry," eds. M.C. Ziskin and P.A. Lewin, CRC Press, Boca Raton, 1993. The transducer is submerged in a tank of water and the ultrasonic beam is directed towards an absorbing or reflecting target in the tank. An absorbing target may be realized by a slab of natural rubber, or a reflecting target by an air-backed thin metal plate. If the ultrasonic beam is directed horizontally, the force can be determined by suspending the target as a pendulum and measuring its deflection. The measurements are made in water because the characteristic acoustic impedances of water and human soft tissue are similar, thus the measured ultrasonic beam power is virtually equal to the power radiated by the transducer into the human body provided that the effect of tissue loss has been accounted for.

It is generally accepted that the radiation force F exerted on a totally absorbing target by an ultrasonic beam of power P is given by the equation

$$F = P/c,$$

where c is the speed of sound in the medium surrounding
the target. For normal incidence on a plane reflecting
surface the radiation force has twice this value. The
speed of sound in water is 1500m/s, thus the radiation
5   force on an absorbing target in water is about 6.67×10^{-4}
newtons/watt.

This sonic radiation force has found application in
medicine in the field of extracorporeal shock wave
lithotripsy. By applying a set of powerful acoustic
10   shock waves at the surface of the patient such that their
energies focus on a target inside the patient, objects
such as renal or gall-stones can be fragmented. Such
lithotripsy systems are described, for example, in
Goldstein, A., "Sources of Ultrasonic Exposure,"
15   Ultrasonic Exposimetry, eds. M.C. Ziskin and P.A. Lewin,
CRC Press, Boca Raton, 1993.

Another application which employs an ultrasonic
radiation force produced by a transducer is disclosed by
Sugimoto et al, "Tissue Hardness Measurement Using The
20   Radiation Force Of Focused Ultrasound", IEEE Ultrasonics
Symposium , pp. 1377-80, 1990. In this experiment, a
pulse of focused ultrasonic radiation is applied to
deform the object which is positioned at the focal point
of the transducer. The deformation is measured using a
25   separate pulse-echo ultrasonic system and the hardness of
the deformed object is measured. Measurements are made
based on the rate of object deformation as the acoustic
force is continuously applied, or by the rate of
relaxation of the deformation after the force is removed.
30   A similar system is disclosed by T. Sato, et al.
"Imaging of Acoustical Nonlinear Parameters and Its
Medical and Industrial Applications: A Viewpoint as
Generalized Percussion", Acoustical Imaging, Vol. 20, pg
9-18, published in 1993 by Plenum Press. In this system
35   a lower frequency wave (350 kHz) is produced to act as a
percussion force, and an ultrasonic wave (5 MHz) is used

-4-

in a pulse echo mode to produce an image of the subject.
The percussion force is said to perturb second order
nonlinear interactions in tissues, which reveal more
structural information than the conventional ultrasonic
5 pulse/echo system alone.

Summary Of The Invention

The present invention is a method and system for
producing an acoustic radiation force at a target
location by directing a high frequency sound beam at the
10 location. The high frequency sound beam is amplitude
modulated and a radiation force is produced at the
location which varies in accordance with the amplitude
modulation.

A general object of the invention is to detect or
15 characterize an object based on its mechanical
properties. An object at the location of the beam will
respond to the applied acoustic radiation force by
producing an acoustic wave that can be detected with a
microphone or other detection apparatus. The detected
20 acoustic wave may be used to detect the presence of the
object or it may be used to detect and evaluate the
mechanical properties of the object.

Another object of the invention is to produce an
image of the target object. The high frequency sound
25 beam may be moved to scan the object and signals
indicative of the acoustic wave produced at each scanned
location may be acquired. The acquired signals are used
to produce an image of the object.

Another object of the invention is to project a
30 force into an object to measure the object's mechanical
characteristics. The radiation force produced by the
high frequency sound beam produces motion at the location
which can be detected and analyzed to measure the
mechanical characteristics at that location. Detection

-5-

can be performed in a number of ways, including Doppler ultrasound and nuclear magnetic resonance imaging.

Yet another object of the invention is to regenerate baseband audio at a remote location. By modulating the high frequency sound beam with a baseband audio signal, the radiation force at the location will vary as a function of the baseband audio signal and a corresponding acoustic wave is produced. By using the highly directional high frequency sound beam, therefore, a non-directional audio wave can be precisely produced at the location.

The foregoing and other objects and advantages of the invention will appear from the following description. In the description, reference is made to the accompanying drawings which form a part hereof, and in which there is shown by way of illustration a preferred embodiment of the invention. Such embodiment does not necessarily represent the full scope of the invention, however, and reference is made therefore to the claims herein for interpreting the scope of the invention.

Brief Description Of The Drawings

Fig. 1 is a block diagram of a first embodiment of the invention used to detect the presence of an object according to the present invention;

Fig. 2 is a block diagram of a second embodiment of the invention used to image an object according to the present invention; and

Fig. 3 is a block diagram of a third embodiment of the invention used to convey a signal acoustically to a distant target object according to the present invention.

General Description Of The Invention

Consider an ultrasonic source directing its beam on a large target in water. The radiation force, F, for the plane wave case is commonly written as

-6-

$$F = KP/c, \tag{1}$$

where P, c, and K are the time averaged acoustic power,
sound speed in water, and a constant, respectively. The
value of K for a perfectly absorbing target is 1, and for
5   a perfectly reflecting target it is 2. For a focused
beam impinging on a partially reflecting target of
arbitrary size, the linear relation of (1) still holds,
however, the value of K is different and can be
determined as a function of target power reflection
10 coefficient and its size as described by J.Wu,
"Calculation of Acoustic Radiation Force Generated by
Focused Beams Using the Ray Acoustic Approach," <u>J.
Acoust. Soc. Am.</u> 97(5), pt. 1, May 1995.

In the present invention the high frequency field is
15 generated by a single, ultrasonic source (single element
or array of elements) driven by an amplitude modulated
signal. The carrier frequency is ω_0 and the modulating
signal, h(t), is defined as:

$$h(t) = \sqrt{u(t)}, \tag{2}$$

20 where
$$u(t) = 1 + f(t). \tag{3}$$

The signal f(t) is a low frequency signal. We assume
$|f(t)| < 1$, also we assume that the bandwidth of f(t) is much
less than the carrier frequency ω_0.
25   We assume the beam is propagating along the z-axis.
The field on the z=0 plane can be written as

$$s(t) = g(x,y) h(t) \cos(\omega_0 t), \tag{4}$$

where g(x,y) is the beam profile on the z=0 plane. It
can be shown that the acoustic power density has slow

-7-

variations about its long time average. Denoting this
component by $P_1(t,x,y)$, we can write

$$P_1(t,x,y) = \frac{1}{2}g^2(x,y)h^2(t).$$ (5)

Assuming a target is present at z=0 plane, then referring
5 to Equation (1), the radiation force exerted on this
target by $P_1(t,x,y)$ may be found by the following
integration:

$$F_1(t) = \frac{K}{c} \int \int P_1(t,x,y)dxdy.$$ (6)

The result of this integration is a function proportional
10 to $h^2(t) = 1+f(t)$. The time-varying component of this
force vibrates the target proportional to the signal
$f(t)$. The target displacement due to this force, $r(t)$,
may be written as

$$r(t) = \frac{1}{2}K'f(t)$$ (7)

15 where K' is a constant whose value depends on size, power
reflection coefficient, and other mechanical parameters
of the target, such as mass and damping factors, that
determine its response to a given force.
      Within the target area the force indicated by
20 Equation (6) will be applied to the object. The manner
in which the object responds to this force will, of
course, depend on its mechanical characteristics. As the
embodiments of the invention described below will
indicate, there are many uses for this invention which
25 stem from its ability to accurately project a low
frequency acoustic force to a defined area.

-8-

The response of an object to the radiation force may be explained by considering a simplified, one-dimensional equation of motion for the mass-spring model. In this model, we assume a mass m is held by a spring having a
5   "stiffness constant" of μ. We also assume that motion of this mass is damped by friction or by other mechanisms represented by the "resistance constant" R_m. Now consider a sinusoidal force $F_1(t) = A\cos\omega_m t$ being applied to this mass. As described by P.M. Morse and K.V. Ingard,
10   "Theoretical Acoustics," McGraw Hill, 1968, the steady-state motion of the mass due to this force can be written as:

$$x(t) = A \cos (\omega_m t + \phi)/\omega_m |Z_m|$$

where

15            $$Z_m = R_m - j (\omega_m - \mu/\omega_m)$$

is the mechanical impedance, and

$$\tan\phi = (\omega_m - \mu/\omega_m)/R_m$$

Thus the amplitude and phase of the displacement of the mass are determined by the mechanical properties m, R_m
20   and μ. At its resonant frequency, where $\omega_m = \sqrt{\mu/m}$, the amplitude of the motion reaches its maximum value.

Description Of The Preferred Embodiment

Referring particularly to Fig. 1, a first embodiment of the invention is used to detect the presence of an
25   object based upon the acoustic wave produced by the object in response to the applied force $F_1(t)$. This detector system includes an ultrasonic transducer 10 which produces a focused beam 14 of beamwidth w = 2mm at

-9-

its focal point. The transducer 10 is driven by an RF
generator 18 that produces an ultrasonic frequency $\omega_0 = 2\pi$
x 3,500,000 rad./sec. This carrier signal ω_0 is applied
to an amplitude modulator 19 which also receives the
5   modulating signal h(t). Here we assume f(t)=cosω_mt, where
$\omega_m << \omega_0$. The modulated carrier is amplified in power
amplifier 20 and applied to the transducer 10.

     The acoustic field produced by the object 21 in
response to the force produced by the focused beam 14 is
10   received by a hydrophone 22. The received signal is
applied through a band-pass filter 24 to an audio
amplifier 26. The band-pass filter 24 has a narrow pass
band centered on ω_m to reject noise and any reflected
ultrasonic signals. The amplified audio signal may be
15   applied to a loudspeaker 28 or an earphone to provide the
operator with an indication of the amplitude of the
acoustic wave produced by the object 21. The transducer
10 can be moved physically to scan the object 21, or in
the alternative the beam 14 can be steered electronically
20   to scan the object 21. An alternative choice for h(t)
can be, for example, h(t)=cosω_mt. In this case, the
acoustic field produced by the object is proportional to
the cos2ω_mt. In this case the band pass filter 24 must be
centered around 2ω_m.

25   A second embodiment of the invention is a novel
imaging system. Rather than relying on the reflection or
attenuation of an ultrasonic wave by the object as is
done in ultrasound imagers, the imager of the present
invention relies on other mechanical properties of the
30   object. More specifically, the ability of the object to
convert the force $F_1(t)$ to an acoustic wave that can be
detected by the receiver.

     Referring particularly to Fig. 2, the imaging system
includes a focused transducer 30 which produces a beam 38
35   which has a focal region from 6 cm to 13 cm, and a
beamwidth of w=2mm (defined as the full-width at half-

-10-

maximum). The transducer 30 is driven by an RF generator
32 which produces a carrier signal $\omega_0 = 2\pi \times 3,500,000$
rad./sec. The carrier signal ω_0 is amplitude modulated at
34 by a modulating signal h(t), and the modulated carrier
5 is amplified by power amplifier 36.

    The sonic wave produced by the target object 42 in
response to the force $F_1(t)$ is received by a hydrophone 44
and digitized. The receiver signal is filtered by a
band-pass filter 46 centered on the frequency of the
10 signal h(t), amplified at audio amplifier 48 and
digitized by a 12-bit analog-to-digital converter 50 at
100,000 samples/sec. The processor 52 calculates the
mean amplitude (or the standard deviation) and/or phase
of 600 samples of the digitized signal, then stores this
15 value in the image array 54 at a location corresponding
to the position of the focal spot of beam 38. Processor
52 also controls other parts of the system to carry out
the scan process. It steers the beam 38 to raster scan
the object 42 in the x-y (or x-z) plane. Beam steering
20 is accomplished either mechanically using two stepper
motors (not shown), or by well known phased array
techniques. Processor 52 also provides the trigger
signals needed to synchronize the scanning and
digitization function. The resulting image produced
25 after a complete raster scan may be enhanced using known
image enhancement methods and/or displayed on a monitor
56. A two-dimensional image is thus produced in which
the gray scale intensity of each pixel indicates the
acoustic level and/or phase produced by the target 42 in
30 response to the applied force $F_1(t)$.

    A variation of this two-dimensional imaging system
can be used to acquire a three-dimensional image in which
two dimensions are spatial (x,z) and the third dimension
is modulation frequency amplitude. In this alternative,
35 the signal f(t) is swept through a range of modulation
frequencies. The acquired signal samples at each x,z

-11-

beam location are stored at successive frequency bins in the image array 54. The resulting frequency dimension provides the information needed for analyzing the spectrum of the object's acoustic response to mechanical
5   stimulations at different frequencies.

As an example application, one can make use of this method to identify calcification in tissue and estimate its thickness and size. Referring to the mass-spring model described above, the amplitude of the motion peaks
10 at the resonant frequency, and this is proportional to

$1/\sqrt{m}$. Calcification with different thicknesses have different masses, thus resonating at different frequencies. Hence, when examining different regions of calcification by the variable modulation frequency
15 method, one can expect to see peaks at different frequency bins depending on the thickness and size of the calcification.

Other imaging modalities can also be used to measure the motion resulting from the radiation force produced by
20 the present invention. For example, a magnetic resonance imaging ("MRI") system, such as that described in co-pending U.S. patent application serial no. 325,834 filed October 19, 1994 and entitled *"MR Imaging Of Synchronous Spin Motions And Strain Waves"* can be used to image the
25 mechanical characteristics of the scanned object. In this system a motion sensitizing magnetic field gradient on the MRI system is synchronized with the applied radiation force (i.e. the signal f(t)) and the resulting motion is precisely indicated by the phase of the
30 acquired NMR signals. As described in this co-pending application which is incorporated herein by reference, nearly all mechanical properties of the imaged object can be measured and used to modulate the intensity of a reconstructed image. This method can be used to provide
35 a map of tissue stiffness which is an excellent tool to

detect deep tumors. Again, an alternative choice for
h(t) is h(t)=cosω_mt in which case the acoustic field is
proportional to cos2ω_mt. In this case the band pass
filter is centered around 2ω_m rather than ω_m.

5   A third embodiment of the invention serves an
entirely different function than those described above.
Rather than obtaining an indication of the presence or
nature of a target object, in the third embodiment of the
invention information is transferred to the target object
10 in the form of acoustical energy. By using an ultrasonic
beam which can be finely focused and directed, this
transfer of information can be precisely targeted.

       Referring particularly to Fig. 3, the audio
regeneration system includes an ultrasound transducer 80
15 that produces a beam 84 which focuses on a target object
88. The beam width at its focal point is w=2mm. The
transducer 80 is driven by an RF generator 90 which
produces a high frequency carrier signal ω_0 at a frequency
of 3.5 MHz. The carrier signal ω_0 is applied to an
20 amplitude modulator 96 which also receives a modulating
signal h(t). The output of the modulator 96
(h(t)cos(ω_0t)) is applied through a power amplifier 94 to
the transducer 80.

       The modulating signal h(t) is produced by a square
25 root circuit 98. It receives as its input the baseband
signal f(t) plus "1". The baseband signal f(t) is less
than "1".

       The ultrasonic beam 84 causes the target object 88
to vibrate in response to the baseband signal f(t). The
30 beam 84 is made very directive because the wavelength of
the ultrasound beam at carrier frequency ω_0 is very small
compared to that of the baseband signal f(t). The target
88 acts as the converter of the high frequency ultrasound
energy to the baseband frequency energy and the frequency
35 response can be made very flat because the bandwidth of

-13-

the baseband signal f(t) is very small relative to the
ultrasound carrier frequency ω_0.

One medical application of this embodiment of the
invention is a hearing aid. The transducer is positioned
5 along side the user's temple and the ultrasonic beam is
directed to structures in the inner ear. The baseband
signal f(t) is the ambient sound picked up by a
microphone and amplified. This ambient sound is
reproduced in the inner ear by vibrating structures in
10 the inner ear. The eardrum and the middle ear are
completely by-passed by this sound regeneration system,
and patients with hearing loss due to problems in these
structures can be helped.

While in many medical applications the transducer is
15 positioned outside the patient and directs ultrasound
into an object in the patient, it is also possible to
place the transducer inside the patient. For example,
the transducer may be mounted on the end of a catheter as
described, for example, in U.S. patent No. 5,345,940 and
20 inserted into the patient through the vascular system.
This enables the transducer to be positioned closer to
the target object.

The invention can be used to remotely measure the
elastic constants of a material. For example, a swept
25 frequency force can be applied to a metallic rod to
measure its resonant frequency. The resonant frequency
can be used to accurately measure the Young's modulus of
the rod material.

The invention can also be used for accurate and
30 remote measurement of the sheer viscosity, or the
density, of a liquid. This can be done by aiming the
ultrasound beam on a well characterized tuning fork
immersed in the liquid. The sheer viscosity or the
density can be measured accurately and remotely by
35 measuring the shift in the resonant frequency of the

-14-

tuning fork with respect to its natural resonant
frequency in vacuum.